

LAND SUBSIDENCE AND AQUIFER-SYSTEM COMPACTION,
SANTA CLARA VALLEY, CALIFORNIA, USA¹

ABSTRACT

Intensive withdrawal of ground water from the confined aquifer system, 800 feet (240 m) thick, in the San Jose area of Santa Clara Valley, California, has drawn down the artesian head as much as 250 feet (75 m) since 1912. Resulting land subsidence, which began about 1915, was 12.7 feet (3.9 m) in 1967.

Periodic leveling of bench marks, core-hole data, and continuous measurements of water-level change and aquifer-system compaction have furnished quantitative evidence on the response of the system to changes in applied stress. The adjusted subsidence-head decline ratio in San Jose for 1920-38 was about 1:10; this ratio can be utilized to estimate ultimate subsidence from subsequent head declines. Compaction records at some sites define the magnitude of excess pore pressures in aquitards; at one site, increasing artesian head by 46 feet (14 m) should stop the subsidence.

INTRODUCTION

The Santa Clara Valley, south of San Francisco, Calif., has the distinction of being the first area in the United States where subsidence due to ground-water withdrawal was recognized and described (Rappleye, 1933). It was first noted when leveling in 1932-1933 of a line of first-order levels established by the US Coast and Geodetic Survey in 1912 showed about 4 feet of subsidence at San Jose. Land subsidence occurs in the central reach of the valley in an area of intensive ground-water development. Discussion in this paper pertains to this central reach, which extends southeastward about 30 miles from Redwood City and Niles to Coyote (fig. 1).

The alluvium-filled valley is a large structural trough lying between the San Andreas fault and the Santa Cruz Mountains on the southwest and the Hayward fault and the Diablo Range on the northeast. (See fig. 1). The alluvial fill includes the semiconsolidated Santa Clara Formation of Pliocene and Pleistocene age and the overlying unconsolidated alluvial and bay deposits of Pleistocene and Holocene age. This fill is as much as 1,500 feet thick; it is tapped by many hundreds of water wells to depths of 500-1,000 feet, and by a few wells as much as 1,200 feet deep.

Fine-grained materials such as clay, silt, and sandy clay, which retard the movement of ground water, constitute the major part of the valley fill. Sand and gravel aquifers predominate near the valley margins where the stream gradients characteristically are steeper. A well-log section from Campbell north to Alviso (Tolman and Poland, 1940, fig. 3) indicates that, to a depth of 500 feet, the deposits at Campbell are about 75 percent gravel and 25 percent clay, but between Agnew and Alviso near the Bay, about 80 percent is clay. Between depths of 600 and 1,000 feet at Agnew, the deposits are about half clay and half gravel.

Below a depth of about 200 feet, ground water is confined by the clay layers, except near the margin of the valley where most of the recharge occurs. Initially, wells flowed as far south as San Jose. Within nearly two-thirds of the valley in the northern part of Santa Clara County, the principal aquifer system is confined.

Well yields in the valley commonly range from 500 to 2,500 gallons a minute. In the triangle between Campbell, Santa Clara, and San Jose, where the aquifer system has the highest transmissivity, the specific capacity of most wells exceeds 100 gpm per foot of drawdown (Calif. Dept. Water Resources, 1967, pl. 6).

DECLINE OF ARTESIAN HEAD

Extraction of ground water from the valley, in acre-feet per year, increased from about 40,000 in 1915 to about 180,000 in the 1960's. Until the middle 1930's, about 90 percent of the extraction was for agricultural use. However, rapid urban expansion since World War II has radically changed the pattern of water use. As a result, by 1967, pumpage for agricultural use had decreased to about 18 percent of the total, and 65 percent was used for municipal supply.

This increasing draft of ground water caused a fairly continuous lowering of the artesian head, which in 1915 was at or above land surface from San Francisco Bay south to San Jose. By the summer of 1965, the artesian head had been drawn down 150-200 feet below the land surface within most of the confined area.

The hydrograph for well 751E-7R1, 840 feet deep, in San Jose (fig. 2) is a representative example of the decline of artesian head from 1915 to 1967. Except for the 75-foot recovery in 1936-1943, during a period of above-normal precipitation, the trend has been generally down, with an overall decline of 185 feet in the 52 years.

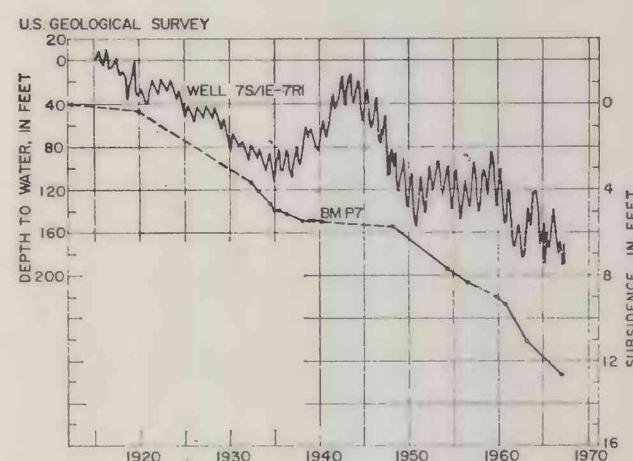


FIGURE 2. Subsidence at bench mark P7 in San Jose and change in artesian head in nearby well LAND SUBSIDENCE

As a result of the excitement caused by the discovery early in 1933 of 4 feet of subsidence at San Jose, a network of level lines was established by the Coast and Geodetic Survey, in collaboration with C.F. Tolman and the writer, to span the area of known and suspected subsidence. This network consisted of a main Y extending north from Coyote to San Jose, with the two arms branching northward from San Jose to Redwood City and to Niles (Poland and Green, 1962, fig. 3). Bedrock ties were established at the terminals of the Y and also at the ends of several transverse lines crossing the valley and the two principal faults. The total length of this level net is about 500 miles. The net has been leveled 12 times; the latest levelings were in 1940 and 1967.

Subsidence from 1934 to 1967 is shown in figure 1. The map was made by computing changes in altitude from 1934 to 1967, at several hundred bench marks, as determined by precise leveling of the Coast and Geodetic Survey, Department of Commerce. Subsidence in the 33-year period exceeded 8 feet in San Jose, and about 100 square miles subsided more than 3 feet. The volume of subsidence from 1934 to 1967 was about half a million acre-feet, equivalent to nearly 3 years of gross pumpage in the 1960's, and about 10 percent of estimated gross pumpage 1934-1967. Thus, about 10 percent of ground-water pumpage in the 33-year period was obtained from compaction of the confined aquifer system. This represents reduction in the pore volume of the ground-water reservoir but the reduction has been principally in the fine-grained compressible aquitards, and therefore should not affect appreciably the storage capacity or the other hydrologic properties of the sand and gravel aquifers.

The subsidence record for bench mark P7 in San Jose (fig. 2) reveals that subsidence in San Jose began before 1920 and increased to 5 feet by 1935. It virtually ceased from 1938 to 1947 during a period of artesian-head recovery. This recovery was the result of above-normal rainfall and recharge; furthermore, natural replenishment was augmented by controlled percolation releases from detention reservoirs constructed in 1935-1936 (Hunt, 1940). By 1948, artesian head had once more declined to the low levels of the middle 1930's and subsidence had recommenced. It reached its most rapid rate of 0.72 foot per year in 1960-1963 in response to the most rapid historic head decline of 1959-1962. By February 1967, subsidence at P7 was 12.7 feet.

SUBSIDENCE PROBLEMS

This subsidence created problems. Lands adjacent to San Francisco Bay have sunk 2 to 8 feet since 1912, requiring construction and raising of levees to restrain the saline Bay water, and flood-control levees near the bayward ends of the valley streams. From Palo Alto around the south end of the Bay are about 30 square miles of evaporation ponds for salt production. Behind the landward chain of dikes bordering these ponds, at least 17 square miles of land lie below the highest tide level of 1967. These lands currently are protected by the dikes and stream-channel levees, but the public cost to 1967 of levee construction due to subsidence was about \$6 million, according to Lloyd Fowler, Chief Engineer of the Santa Clara County Flood Control and Water District. The subsidence has affected stream channels in two ways. Bay water has moved upstream and channel grades crossing the subsidence bowl have been downwarped. Both of these changes tend to cause channel deposition near the Bay and reduce channel capacity, thus creating the need for higher levees. Even though levee heights have been raised, flooding behind the Bay levees occurs at times of excessive runoff.

When the sediments in the confined aquifer compact to produce the subsidence, well casings are compressed and many have been ruptured. Protrusion of casings as much as 2-3 feet above land surface also has been observed (Tolman, 1937, p. 344). Several hundred

well casings have been repaired and many new wells have been drilled to replace wells destroyed by compaction. Roll (1967) estimated the cost of this well repair and replacement as at least \$4 million.

CORE HOLES

In 1960, the Geological Survey drilled two core holes at the two centers of subsidence in San Jose and Sunnyvale (fig. 1), to a depth of 1,000 feet—the maximum depth tapped by nearby water wells. Cores were tested in the laboratory for particle-size distribution, dry unit weight, specific gravity of solids, porosity, permeability (vertical and horizontal), Atterberg limits, and consolidation and rebound (Johnson, Moston, and Morris, 1968). Meade (1967) determined the clay-mineral assemblage for 20 core samples by X-ray diffraction methods and found the average composition to be 70 percent montmorillonite, 20 percent chlorite, and 5-10 percent illite.

COMPRESSIBILITY OF THE FINE-GRAINED SEDIMENTS

The compressibility of the fine-grained clayey sediments is a basic parameter in determining how much compaction and subsidence would occur ultimately in response to a given decline in artesian head. The compressibilities of 10 cores from the Sunnyvale hole, ranging in depth from 191 to 865 feet, have been computed from one-dimensional consolidation tests and are plotted in figure 3. This graph shows that at an effective stress of 260 psi (18.3 kg per cm²), the native stress at mid-depth of the aquifer system, the range in compressibility of the 10 samples is 2.3 to 3.4 × 10⁻⁴ psi⁻¹ (3.3 to 4.8 × 10⁻³ cm² per kg). The compressibility of these samples is about 3 times as great at 160 psi (11.3 kg per cm²) (1960 effective stress at top of aquifer system) as at 490 psi (34 kg per cm²) (stress at base of aquifer system). For the compressibility-effective stress log-log plots for the eight cores that are closely grouped in figure 3, the equation of the average compressibility-effective stress line is

$$m_p = 0.053 p^{-0.93}$$

where:

m_p is the coefficient of volume compressibility in psi⁻¹, and
 p' is effective stress in psi.

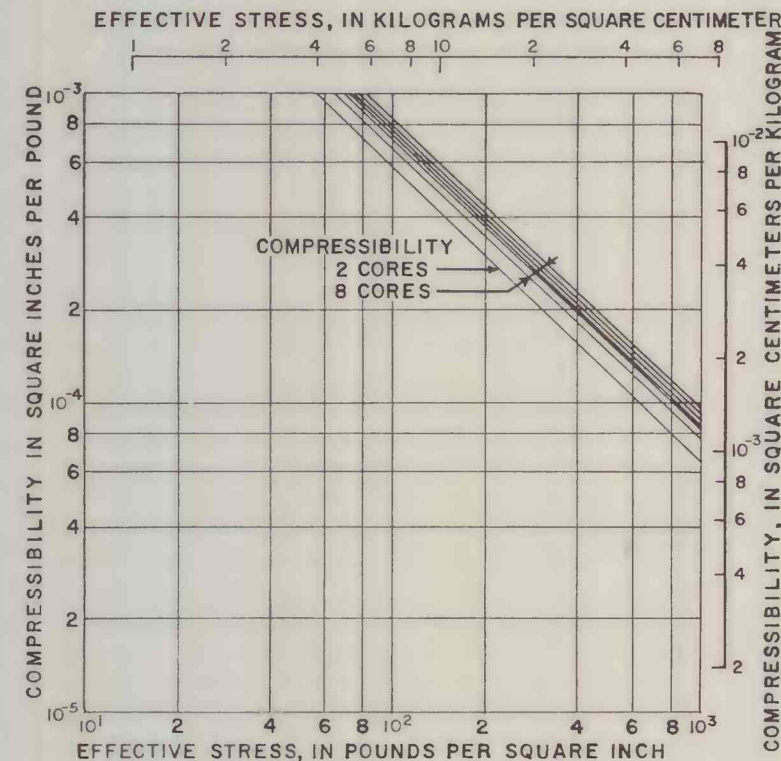


FIGURE 3. Compressibility of fine-grained samples, Sunnyvale core hole

When the compressibility curves of the fine-grained aquitards or aquicludes are as closely bunched as those at Sunnyvale, the approximate ultimate subsidence (Δz) for a given increase in stress can be computed, utilizing the equation

$$\Delta z = m_p \Delta p'$$

where:

m_p is average compressibility,
 m is aggregate thickness of compacting beds, and
 $\Delta p'$ is change in effective stress.

However, because compressibility does not decrease linearly with increasing stress, and the fine-grained beds are not uniformly distributed, the well section should be divided into zones not more than 200 feet thick, and the average compressibility for each zone should be read from the plot, for the mean effective stress.

$$\frac{2p_0 + \Delta p'}{2}$$

where:

p_0' is the initial effective stress at the midpoint of the zone, and
 $\Delta p'$ is the increase in stress induced by artesian-head decline.

COMPACTION OF THE AQUIFER SYSTEM

Compaction recorders of the type described by Lofgren (1970) have been operated in the core holes since 1960 to measure the magnitude and rate of compaction. Figure 4 shows the record of compaction at Sunnyvale through 1968, including compaction in the 1,000-foot core hole (well 24C7) and in two satellite wells 250 and 550 feet deep. It also shows artesian-head fluctuation in well 24C7 (casing perforated only in aquifers below a depth of 800 feet) and in irrigation well 25C1 (depth 500 feet). Subsidence of the land surface at nearby bench mark JIII from 1933 to 1960 was 5.73 feet, and estimated subsidence 1915-1960 was 8.7 feet. Subsidence of this bench mark from October 1960 to February 1967,

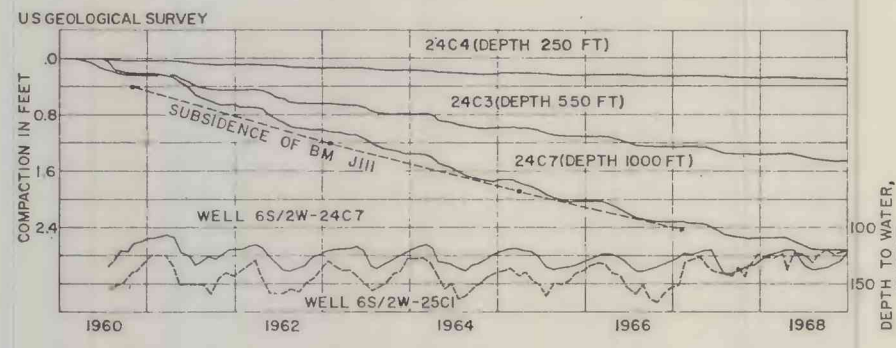


FIGURE 4. Measured compaction, water-level change, and subsidence in Sunnyvale as measured by leveling of the Coast and Geodetic Survey, was 2.03 feet. Compaction of the aquifer system to the 1,000-foot depth as measured in 24C7 in the same time interval was 2.13 feet. The 5 percent excess measured compaction is attributed to instrumental error in the earlier years of operation. Surface leveling and measured compaction from April 1965 to February 1967 agreed within 0.01 foot. Therefore it is concluded that land subsidence at this site is due entirely to aquifer-system compaction to the 1,000-foot depth.

The unit compaction of the fine-grained beds at the Sunnyvale site, 1961-1968 inclusive, is tabulated below.

It is assumed that the measured compaction occurred entirely in the fine-grained clayey beds, which here constitute 88 percent of the confined aquifer system. The unit compaction, 1961-1968, in the deepest interval was about 60 percent of that in the uppermost interval, 168-250 feet below the land surface.

Figure 5 shows the measured compaction in the San Jose core hole (well 16C6) and the compaction and artesian-head fluctuation in nearby unused well 16C5 (depth 908 feet)

Well	Depth (feet)	Total Compaction 1961-1968 (feet)	Depth interval (feet)	Compaction (feet)	Fine-grained beds thickness in interval (feet)	Unit compaction (feet)
24C7	1,000	2.50	550-1,000	1.32	432	3.05 × 10 ⁻⁴
24C3	550	1.18	250- 550	0.92	244	3.75 × 10 ⁻⁴
24C4	250	0.26	*168- 250	0.26	52	5.00 × 10 ⁻⁴

* Midpoint of upper confining bed is 168 feet.

through 1968. Total measured compaction of the aquifer system from July 1, 1960, to December 31, 1968, was 4.42 feet. The rapid decline of artesian head from 1959 to 1962 (60 feet) caused rapid compaction of the aquifer system in those years but the rate decreased during the relatively consistent head fluctuation from 1962 to 1967. The 30-foot recovery of head in the spring of 1968 above the 1967 high caused a net expansion of the aquifer system (0.06 foot) for the first time since the compaction recorders were established in 1960.

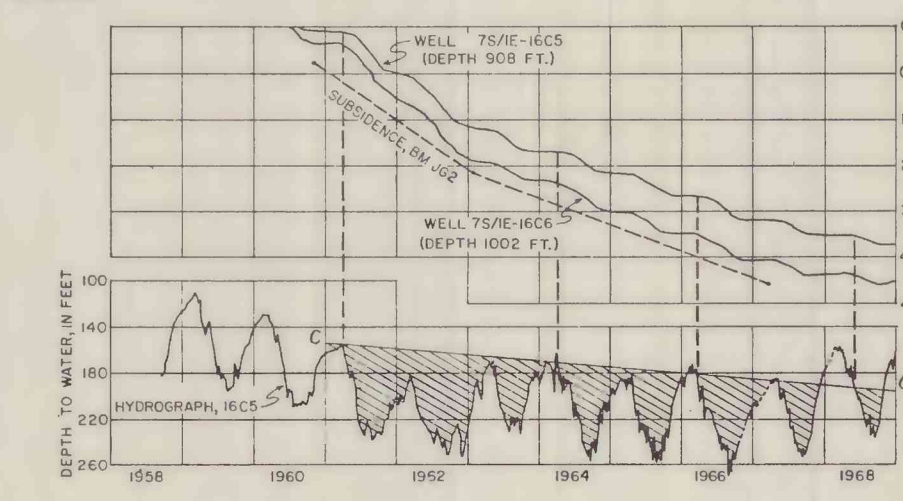


FIGURE 5. Measured compaction, water-level change, and subsidence in San Jose A stress-strain plot of head versus compaction (not shown) indicates that response was entirely elastic for head fluctuations in the 160-190-foot depth range. The slope of the elastic-response line indicates that the component of the storage coefficient attributable to elastic response of the confined aquifer system skeleton (depth interval 200-1,000 feet) is 1.25 × 10⁻³. Thus, the component of specific storage attributable to elastic response of the confined system skeleton is 1.6 × 10⁻⁴ (3.25 × 10⁻³ cm² per kg) and the gross elastic compressibility is 3.7 × 10⁻⁵ psi⁻¹ (5.25 × 10⁻³ cm² per kg).

Response of the system was wholly elastic for artesian-head change above the 190-foot depth to water in 1968. Therefore, maximum excess pore pressures in the aquitards must have been completely eliminated when the head in the aquifers rose to 190 feet below the land surface. Utilizing the compaction records for 1961, 1964, and 1966, when compaction stopped at peak winter rise, a line has been drawn on the hydrograph of well 16C5 to define the approximate depth to water at which excess pore pressures were eliminated (line C-C'). The shaded area beneath this line defines the variation in magnitude of maximum excess pore pressures in the aquitards from 1961 to 1968. As of 1968, a net rise of 46 feet in the summer low water level would eliminate all permanent compaction and stop land subsidence.

The response of the system shown by the long-term subsidence graph of bench mark P7 and the head change in nearby well 7R1 (fig. 2) can be utilized to estimate ultimate subsidence from head change since 1938. From 1920 to 1938, when subsidence stopped, 50 feet of net head decline from about 30 to 80 feet below land surface caused 5 feet of subsidence. The gross plastic-plus-elastic compressibility of the 800-foot thickness of the compacting aquifer system derived from this stress-strain relation is 5 ft/800 ft × 21.6 psi or 2.9 × 10⁻⁴ psi⁻¹ (4.1 × 10⁻³ cm² per kg). The subsidence/head decline ratio for the period from 1920 to the steady-state conditions of 1938 (no compaction) was 5.0/50 or 1:10. The subsequent head decline of 100 feet below 1938 levels by 1967 had produced 7.3 feet of additional subsidence, but decay of excess pore pressures in the aquitards was causing continued subsidence. The product of the gross compressibility (derived from the 1920-38 step change), the aquifer-system thickness, and the change in applied stress (100 feet of decline) is 10 feet, suggesting that roughly 2.7 feet of residual compaction and subsidence would occur at this site if artesian head remained at a depth of 180 feet. Obviously, an estimate so derived is only a rough approximation, because the assumption is made that gross compressibility would remain constant under the additional stress of 43 psi. At mid-depth of the system (600 feet), the reduction in plastic compressibility due to this increase in stress would be about 10 percent. It is of interest to note that the computed gross plastic-plus-elastic compressibility at bench mark P7 is 78 times as large as the gross elastic compressibility at well 16C6.

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ADDENDUM 1971

The land subsidence in Santa Clara Valley, between Palo Alto and southern San Jose, is unique for several reasons:

- (1) It was the first area in the United States where land subsidence due to ground-water overdraft was recognized (in 1933).
- (2) It was stopped once around 1940, due to water-level recovery resulting largely from nature's above-normal precipitation and runoff.
- (3) It has been virtually stopped again as of 1971, but this time by man's reversal of the water-level decline, primarily through a water-import program.

The Santa Clara County Flood Control and Water District estimates that about \$9 million of public funds has been spent on levee construction and other remedial work on stream channels to prevent flooding as a result of land subsidence, especially along the southern shore of San Francisco Bay.

In addition, the Leslie Salt Co. has spent an unknown but substantial amount on raising and maintenance of its salt-pond levees, due to subsidence.

Several hundred water-well casings have been ruptured by the compaction of the sediments. The cost of repair or replacement of such damaged wells has been estimated as at least \$4 million.

From Palo Alto around the south end of the Bay are about 30 square miles of evaporation ponds for salt production. Behind the landward chain of dikes bordering these ponds, at least 17 square miles of land lies below the highest tide level of 1967 as a result of the subsidence. This condition creates problems in development of the area.

Both the cause of this subsidence and the means of control are known. The evidence given here and other studies by the Geological Survey prove that the subsidence is caused by decline of the artesian head and the resulting increase in effective overburden load or grain-to-grain stress on the water-bearing beds. The sediments compact under the increasing stress and the land surface sinks. Most of the compaction occurs in the fine-grained clayey beds (aquitards) which are the most compressible but have low permeability. Therefore, the escape of water (decay of excess pore pressure) and the increase in effective stress are slow and time-dependent, but the ultimate compaction is large and chiefly permanent.

The subsidence can be stopped by raising the artesian head in the aquifers until it exceeds the residual excess pore pressure in the aquitards. Between 1967 and March 1971, the dramatic recovery of artesian head has cancelled most of these excess pore pressures and subsidence has virtually ceased. The compaction and water-level records being obtained by the Geological Survey indicate that if management can raise and maintain artesian head at least 20 feet above present levels, subsidence can be stopped permanently.

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT

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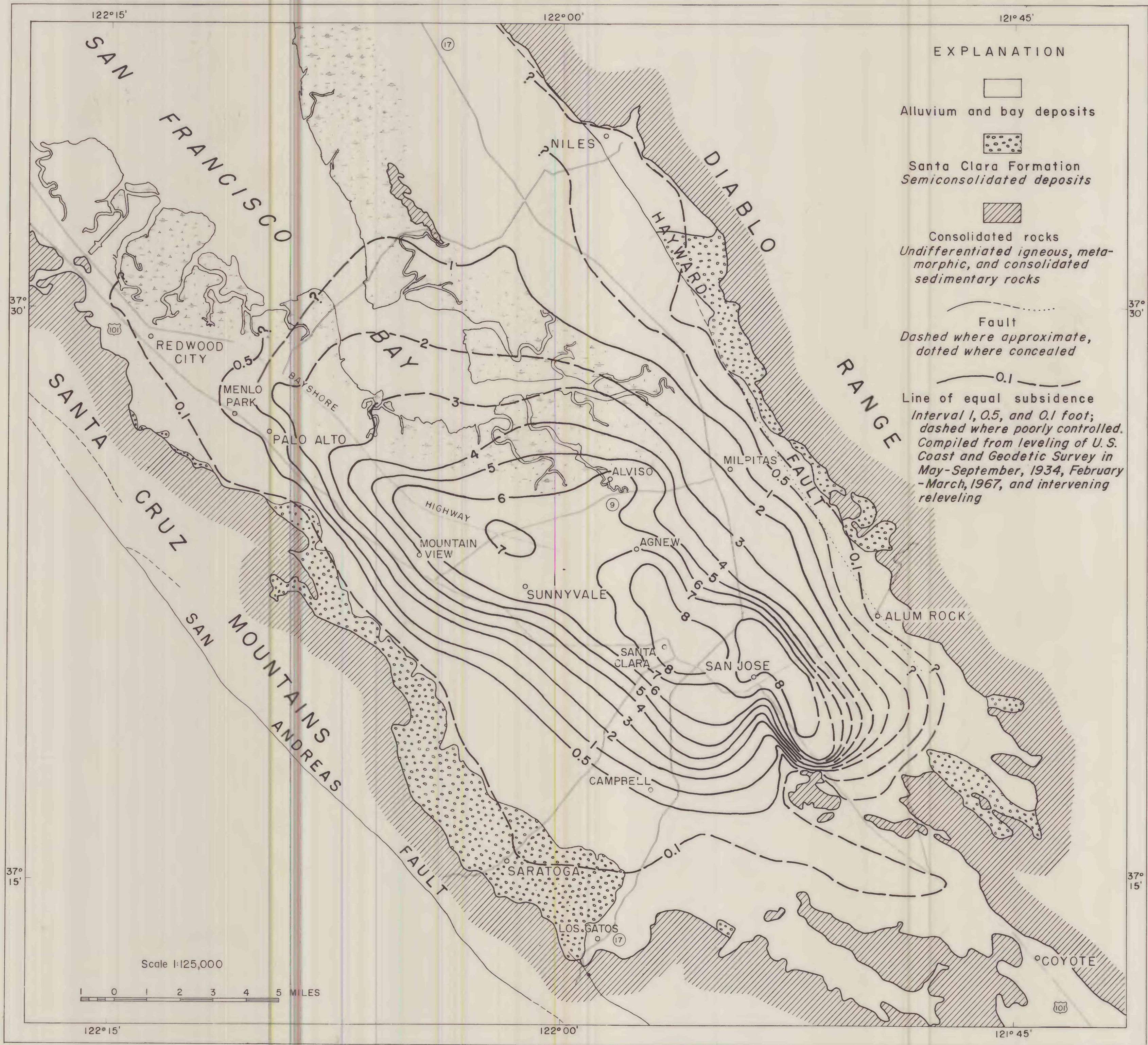


Figure 1. LAND SUBSIDENCE FROM 1934 TO 1967, SANTA CLARA VALLEY, CALIFORNIA

Compiled by J. F. Poland and R. L. Ireland, March 1968

LAND SUBSIDENCE IN THE SANTA CLARA VALLEY,
ALAMEDA, SAN MATEO, AND SANTA CLARA COUNTIES, CALIFORNIA

by
J. F. Poland
1971

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